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1   **Magma-Hydrothermal Interactions at the Costa Rica Rift from Data Collected in 1994 and**

2   **2015**

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16

17   **Abstract**

18

19   We use co-located CTD/transmissometry casts and multichannel seismic reflection surveys

20   conducted at the Costa Rica Rift (CRR) to provide a better understanding of magma-

21   hydrothermal processes occurring at an intermediate-rate spreading center. Water column

22   observations reveal an ~200 m thick plume head ~650 m above the seafloor, which corresponds

23   to a hydrothermal heat output of ~200 ± 100 MW at the ridge axis. Assuming a hydrothermal

24   vent temperature of 350°C and a discharge area between 10^4 and 10^5 m^2, this heat output implies

25   a mean crustal permeability within the discharge zone of between 2 x 10^{-14} and 6 x 10^{-13} m^2, and

26   a conductive thermal boundary layer thickness of ~20 m. The volume of magma required to

27   maintain the current hydrothermal heat output over the past two decades should result in an

28   across-axis axial magma lens (AML) width between 270 and 1300 m, depending on the amount

29   of cooling and crystallization. However, seismic reflection images, acquired in 1994 and 2015,

30   while showing an apparent along-axis growth of the AML from 2.4 to 6.0 km between surveys,

31   also suggest that, as of 2015, the AML has an apparent across-axis width of no more than 300 m,

32   and that magma delivery at the intermediate spreading rate CRR may be episodic on time scales

33   of tens of years. The data on magma-hydrothermal interactions at the CRR collected in 1994 and

34   2015 suggest that the hydrothermal system may have significantly cooled and crystallized the

35   AML, primarily in the across-axis direction, and that this hydrothermal system may also

36   episodically turn on and off. The current pattern of microseismicity supports this conclusion,

37   with events not only mirroring the AML depth and location beneath the ridge axis, but also

38   having a temporally varying focus.

39

1. Introduction

An aim of the OSCAR project (*Oceanographic and Seismic Characterization of heat dissipation and alteration by hydrothermal fluids at an Axial Ridge*) was to develop a basin-scale model of deep ocean circulation. To this end, a large-scale interdisciplinary geophysical and oceanographic exploration of the Panama Basin, in the eastern Pacific, was conducted between December 2014 and March 2015. A key part of this program focused on the east-west trending, intermediate spreading rate Costa Rica Rift (CRR) (Figure 1), which runs from 3°20′N, 84°11′W to 3°19′N, 83°15′W and is characterized by a 103 km-long rift valley bounded by the Ecuador Fracture Zone to the west and the Panama Fracture Zone to the east. The CRR is asymmetrically spreading with a half rate of 20-25 mm yr^{-1} to the north (the Cocos Plate) and 35-40 mm yr^{-1} to the south (the Nazca Plate) [*Wilson et al.*, 2019]. At 3°20′N, 83°44′W, the ridge is divided into two second-order segments by a small non-transform discontinuity (NTD), where the two segment tips overlap by 2.4 km and are offset by ~1.5 km laterally.

In 1994, RV Maurice Ewing cruise EW9416 imaged a seismic reflector (~2.8 km depth) beneath the bathymetrically shallowest seafloor at the ridge axis (~2900 m below sea level) approximately ~10 km west of the NTD [*Buck et al.*, 1997; *Floyd et al.*, 2002]. In common with seismic reflection studies at other oceanic spreading centers over a range of spreading rates [e.g., *Detrick et al.*, 1987; *Navin et al.*, 1998; *Canales et al.*, 2006; *Singh et al.*, 2006; *Jacobs et al.*, 2007; *Van Ark et al.*, 2007; *Carbotte et al.*, 2013] this reflector was interpreted as evidence of an axial magma lens (AML). As such, this location offered an ideal target to investigate the

62   relationship between crustal heat flow, heat output to the water column, the nature of the heat

63   source and how hydrothermal fluid flow is sustained.

64

65   Consequently, during OSCAR cruise RRS James Cook JC112/113, a number of conductivity,

66   temperature and transmissometry versus depth measurements (henceforth referred to as CTTD

67   data) were made in the water column above the location of the EW9416 seismic line and in the

68   vicinity of the CRR axis [*Banyte et al.*, 2018]. The goal of the CTTD casts was to determine

69   whether there was evidence of current hydrothermal activity in the water column at the ridge

70   axis. Water samples were also collected to determine the ^{3}He distribution in the water column, in

71   order to characterize and determine the distribution of any hydrothermal emissions.

72

73   In addition, the 1994 multichannel seismic (MCS) survey was also repeated during OSCAR

74   cruise RRS James Cook JC114 [*Hobbs and Peirce*, 2015] to appraise the AML's temporal

75   characteristics and to better constrain its dimensions and extent along-axis. As part of this survey

76   a 3D grid of ocean-bottom seismographs (OBSs) was also deployed across the CRR to provide a

77   ridge-axis velocity model to enable depth conversion [*Zhang et al.,* 2016; 2017]. A vertical array

78   of hydrophones recorded the down-going seismic waveform to enable source signature matching

79   to the 1994 data. MCS lines perpendicular to the ridge axis were also acquired during JC114 to

80   determine the across axis width of the AML (Figure 1); and a transect to the ODP 504B borehole

81   was acquired to provide geophysical versus geological ground truth [*Wilson et al.*, 2019].

82

83   In this paper, we describe the results of co-located water column measurements and seismic

84   reflection images acquired at the CRR, and provide new insights into the coupled magma-

85   hydrothermal interactions at this intermediate spreading ridge system (Figure 2). We apply

86   buoyant plume theory to estimate the heat output of the hydrothermal plume, and use the single

87   pass model [e.g., *Lowell and Germanovich*, 2004; *Lowell et al.*, 2013] to estimate the mass flow

88   rate and crustal permeability at the CRR axis. By combining our heat output estimates with the

89   observed dimensions and extent of the AML in 1994 and 2015, we appraise the role played by

90   the AML in driving hydrothermal circulation. Finally, we speculate on the nature and longevity

91   of hydrothermal fluid flow at the CRR.

92

93   **2. Oceanographic observations of the hydrothermal system**

94

95   Transmissometry data from seven CTTD casts at and near the axis of the CRR (Figure 3a)

96   indicate that there is a measurable decrease in beam transmission over a 200 m-deep zone with

97   its top located ~650 m above the 3150 m-deep seafloor. We interpret this decrease in beam

98   transmission as resulting from a higher concentration of particulate matter within this zone,

99   indicative of a hydrothermal plume reaching neutral buoyancy at this height above seafloor [e.g.,

100   *Baker et al.*, 1985; *Baker and Massoth*, 1987]. Evidence for the presence of hydrothermal

101   activity is also provided by helium isotope data at ocean ridges [e.g., *Lupton*, 1998]. Here the

102   data show an ~50% increase in ^{3}He concentration at an equivalent depth, compared to

103   background values in the surrounding area (Figure 3b).

104

105   As a hot hydrothermal plume buoyantly ascends from the seafloor it entrains surrounding

106   seawater. As a result of fluid phase separation in the sub-seafloor, the salinity of plume water

107   may be different to that of seawater. The ascending mixture of hydrothermal plume fluid and

5

108   entrained seawater will gradually reach a level of neutral buoyancy and will then spread laterally

109   [e.g., *Turner and Campbell*, 1987]. The maximum rise height of the plume is a function of the

110   buoyancy flux and the density structure of the ocean above, which is described by the Brunt-

111   Väisälä, or buoyancy, frequency N. The Brunt–Väisälä frequency is defined as $N = \sqrt{-g\,\rho_z/\rho}$,

112   where g is the acceleration due to gravity, ρ is potential density, and ρ_z denotes the partial

113   derivative of ρ with respect to the vertical coordinate, z. We calculate ρ from the CTTD

114   potential temperature, conductivity/salinity and pressure data using the Thermodynamic

115   Equation of Seawater -2010 (TEOS-10) formulation [*IOC et al.*, 2010]. From the maximum rise

116   height of the plume Z^* can be expressed by [*Turner and Campbell*, 1987],

117

118     $$Z^* = 3.8 F_0^{1/4} N^{-3/4}\,, \tag{1}$$

119

120   where the numerical factor 3.8 represents an average rate of entrainment over the height of the

121   plume as derived from a number of laboratory experiments [*Turner*, 1986]. The buoyancy flux

122   F_0 is defined as,

123

124     $$F_0 = Q \frac{\Delta\rho}{\rho_0} g\,, \tag{2}$$

125

126   where Q is the volume flow rate in $m^3\ s^{-1}$ and $\Delta\rho$ is the density difference between hydrothermal

127   fluid and seawater. Symbols and parameter values are given in Table 1. Although $\Delta\rho/\rho_0$ may

128   result from both salinity and temperature differences, here we assume that the primary factor is

129   the difference in temperature. Hence,

130

131     $\Delta\rho/\rho_0 = \alpha\Delta T$,

132

133   where α is the thermal expansion coefficient of seawater. Given that the heat output, H, in the

134   hydrothermal plume is,

135

136     $H = \rho c_p Q\Delta T$,   (3)

137

138   where c_p is the specific heat at constant pressure, the heat output can then be written in terms of

139   the buoyancy flux F_0 or the maximum plume rise height, Z^*, as

140

141     $$H = \frac{\rho c_p}{\alpha g} F_0 = \frac{\rho c_p}{\alpha g}\left(\frac{Z^*}{3.8}\right)^4 N^3.$$

                                                                  (4)

142

143   The strong dependence of H on Z^* and N suggests that small errors in these parameters can lead

144   to significant errors in the estimated value of H.

145

146   Figure 3c shows the abyssal density stratification, N^2, determined from the CTTD casts

147   undertaken at the CRR axis, plotted with depth. The graph shows that N^2 gradually increases

148   with height above seabed, with a sharp change in gradient near 2500 m depth. This depth, which

149   coincides with the top of the zone of decreased transmissivity and interpreted as the top of a

150   hydrothermal plume head (Figure 3a), likely results from a change in ocean dynamics at depths

151   less than 2500 m. The average value of N^2 between 3150 m and 2500 m depth is $\sim 2 \times 10^{-7}$ s^{-2}.

152

153   Using parameter values from Table 1, a maximum rise height for the plume, and a Z^* of ~650 m,

154   we obtain a heat output, H, of ~200 ± 100 MW. Uncertainties in H stem from uncertainties in Z^*

155   (±10 m), N^2 (±0.5 x 10-7 s^{-2}), and the average value of N^2 at the relevant depth of 0.25 x 10^{-6} s^{-2}

156   (Figure 3c). This heat output is similar to estimates for hydrothermal systems at other mid-ocean

157   ridges [e.g., *Baker*, 2007], and suggests that the observed CRR plume likely results from a high-

158   temperature black smoker-like system. Data from seafloor hydrothermal systems indicate that

159   although most of the heat output occurs in the form of diffuse flow, 80-90% of hydrothermal

160   heat output is derived from high-temperature magma driven flow [Mittlelstaedt et al., 2012;

161   Lowell et al., 2013].

162

163   Although direct measurements of the hydrothermal vent temperature at the CRR are not

164   available, black smoker temperatures are typically ~350°C [e.g., *Lowell et al.*, 2013]. Using a ΔT

165   value of 350°C, equation (3) yields a volumetric flow rate of $0.1 \leq Q \leq 0.2$ m^3 s^{-1}. Assuming that

166   this flow is driven by buoyancy differences between cold recharge fluid and hot vent fluid within

167   the permeable crust, an integrated expression of Darcy's Law (assuming that the main resistance

168   to hydrothermal flow occurs in the discharge zone) enables an estimate of crustal permeability to

169   be made using,

170

171    $$Q = \frac{\alpha_d g k_d T_v A_d}{v_d},$$ (5)

172

173   where k_d is the permeability, T_v is the mean vent temperature, A_d is the area of the discharge

174   zone, and v_d is the kinematic viscosity. The subscript d is used to indicate properties of the

175   discharge zone.

176

177   Substituting the above values for Q into equation (5) together with the parameter values from

178   Table 1, we obtain $2 \times 10^{-9} \leq k_d A_d \leq 6 \times 10^{-9}$ m^4. Given that the footprint areas of vent fields are

179   typically observed to lie between 10^4 and 10^5 m^2 [e.g., *Lowell et al.*, 2013], we estimate that the

180   crustal permeability in the CRR hydrothermal discharge region lies between 2×10^{-14} and $6 \times$

181   10^{-13} m^2, similar to that estimated for many seafloor systems [*Lowell et al.*, 2013].

182

183   Having determined the amount of heat being output into the water column at the CRR, we can

184   now use this estimate to provide an insight into the nature of the heat source, by determining the

185   extent and temporal characteristics of the axial magmatic system as evidenced by the observed

186   AML.

187

188   **3. Seismic observations of the AML**

189

190   To enable direct comparison of the 1994 [along-axis line 1268 (EW9416)] and 2015 [along-axis

191   line NG_Bb13 and across-axis line NG_G10 (JC114)] MCS lines, all lines have been processed

192   in an identical manner to final migrated form [*Zhang et al.,* 2017]. Details of the acquisition can

193   be found in the JC114 cruise report [*Hobbs and Peirce*, 2015] and the processing sequence

194   included: trace editing, divergence correction and amplitude balancing, band-pass filtering,

195   Kirchhoff pre-stack time migration, muting, stacking, and noise suppression. To maintain

196   consistency in data processing between surveys, the pre-stack time migration of both along-axis

197   lines was applied with the same velocity model, which was based on the velocity analysis of line

198   1268, and waveform matching between the 1994 and 2015 surveys was applied based on the

199   vertical hydrophone recording of the down-going waveform during JC114. MCS image depth

200   conversion was undertaken using a sub-seabed velocity structure and was derived from modeling of

201   OBS and MCS gather travel-time picks [*Wilson et al.*, 2019; *Robinson et al.*, in revision].

202

203   Both MCS surveys image an AML at approximately the same two-way travel time (TWTT) sub-

204   seabed (Figure 4). The reprocessed line 1268 from the original 1994 survey (Figure 4a), shows a

205   2.4 km-long reflection event at 5.1 to 5.3 s two-way travel time (TWTT). The 2.38 km s^{-1}

206   stacking velocity of this event precludes it from being a water-path scattered event or a sea

207   surface/water bottom multiple. Modeling of the near-offset traces in the unstacked gathers

208   (Figure 5) shows that the reflection event corresponds to a thin, low velocity anomaly, where the

209   velocity may be as low as 4.5 km s^{-1}, and where its thickness may be of the order of ~100 m.

210   Using the background upper crustal velocity model, the AML imaged in 1994 has an apparent

211   eastward dip, lying between 3.0-3.5 km below the seafloor.

212

213   Line NG_Bb13, from the more recent 2015 resurvey, was navigated to the location of line 1268

214   to better than the Fresnel radius of ~500 m at AML depth, assuming a dominant frequency of 20

215   Hz. This line (Figure 4b) also images the AML reflection at 5.1 to 5.3 s TWTT (3.0-3.5 km

216   below the seafloor), suggesting a consistency of melt supply to the ridge-axis with at least an

217   ~20-year episodicity, that also arrives at 5.1 to 5.3 s TWTT (3.0-3.5 km below the seafloor). This

218   reflection event has a total length of ~6 km, where the additional length results from an extension

219   westward from the AML as originally imaged in 1994. Along-axis variation in reflection true

220   amplitude suggests that, as of 2015, the AML may possibly be split into two limbs, with a gap of

221   ~600 m between them (Figure 4b). The eastern limb effectively mirrors that of line 1268, but

222   extends westward for ~650 m, whereas the western limb, which is only observed on line

223   NG_Bb13, extends the AML an additional 2.5 km.

224

225   AMLs detected along the intermediate spreading Juan de Fuca Ridge [*Van Ark et al.*, 2007] and

226   the fast spreading East Pacific Rise [*Carbotte et al.*, 2013], typically have an across-axis width of

227   between ~500 and 1000 m. However, the orthogonal line NG_G10 (Figure 4c) from the 2015

228   survey does not show a similar expression of an AML reflection event. This observation at the

229   CRR may indicate that the width of the AML is similar to the lateral resolution of the seismic

230   signal which, for the 20 Hz peak frequency, suggests a width of no more than ~60 m. The line

231   NG_G10 image possibly shows a narrow-width event whose diffraction would intersect line

232   NG_Bb13 at the time of the imaged AML reflection. The event is no more than 300 m wide,

233   which we assume as an estimate for the maximum-width case analyzed below. The apparently

234   narrow width of the AML at the CRR could possibly indicate enhanced lateral hydrothermal

235   circulation that rapidly freezes the melt lens in both off-axis directions. Based on the above we

236   estimate the areal extent of the AML, as of 2015, to be less than ~1.8 x 10^6 m^2.

237

238   **4. Link between AML and hydrothermal heat output**

239

240   Using the estimated heat output at the CRR of ~200 MW and an estimated magma heat transfer

241   area (A_m) of 1.8 x 10^6 m^2, we construct a simple heat balance model for heat transfer from the

242 AML to the hydrothermal system. We assume conduction across a thermal boundary layer of

243 thickness, δ, following *Lowell and Germanovich* [2004] and *Lowell et al.* [2013],

244

245 $$H = \frac{\lambda(T_m - T_v/2)A_m}{\delta},$$ (6)

246

247 where λ is the thermal conductivity of the host rock, and T_m is the mean temperature of the

248 AML. Using parameters defined in Table 1, and the subscript m to indicate properties of the

249 magma, we obtain a thermal boundary layer of thickness of ~20 m, similar to estimates for other

250 ridge axis systems [*Lowell et al.*, 2013] and ophiolites and tectonic windows [e.g., *Gillis*, 2008].

251 Our estimated uncertainty in δ is ± 10 m primarily based on the uncertainty in H and we note that

252 the thermal boundary layer thickness scales linearly with A_m, so a smaller A_m would yield a

253 smaller δ.

254

255 However, to maintain the estimated heat output in a quasi-steady-state, this thermal boundary

256 layer must retain an effectively constant thickness [*Lowell and Germanovich*, 2004] which, in

257 turn, necessitates the influx of fresh magma into the AML [*Liu and Lowell*, 2009; *Choi and*

258 *Lowell*, 2015]. Following *Lowell et al.* [2013] we assume that the observed hydrothermal heat

259 output is driven by heat transfer from the magma that has replenished the AML, cooled and

260 partially crystalized between 1994 and 2015. The mean rate of magma replenishment, dV_m/dt,

261 needed to maintain a hydrothermal heat output can be written as,

262

263 $$H = (\rho_m c_m \Delta T + \rho_m \chi L)(dV_m/dt),$$ (7)

264

265 where χ is the crystal fraction, and the first term in parenthesis on the right side of equation (7) is

266 the sum of the sensible and latent heat released as the melt cools and crystallizes. Although the

267 MCS data do not provide direct information regarding the state of the AML volume, internal

268 temperature and crystal content, the images do show that the AML still exists where it was first

269 imaged in 1994, and further show that it has apparently doubled in length, largely westwards.

270 Hence the MCS data suggest magma replenishment and AML growth between 1994 and 2015,

271 either constantly or episodically, since in this time frame the AML imaged in 1994 would

272 otherwise have solidified, and hydrothermal heat output that may have been present in 1994

273 would have declined. Without magma replenishment, crystal suspended simulations of AML

274 cooling show a rapid decrease in heat output and hydrothermal temperature such that

275 crystallinity reaches 60% in less than 10 years [*Liu and Lowell*, 2009].

276

277 Although mid-ocean ridge magma supply shows variability on decadal time scales, we start by

278 estimating the mean rate of magma replenishment required to maintain the hydrothermal system

279 at a quasi-steady-state heat output of 200 MW for the past two decades. We assume quasi-

280 steady-state input magma at its liquidus temperature. For simplicity, we further assume that each

281 initial cooling of 10°C leads to 5% fractional crystallization [*Maclennan*, 2008; *Lowell et al.*,

282 2013]. If magmatic heat transfer is accompanied by cooling of 20°C, as observed at 9°50′N at the

283 East Pacific Rise between the eruptions of 1991/1992 and 2005/2006 [*Goss et al.*, 2010], the heat

284 released by cooling of the replenished magma is $\sim$60 MJ m^{-3} + $\sim$110 MJ m^{-3}, corresponding to

285 the sensible and latent heat respectively, or $\sim$170 MJ m^{-3} in total. Substituting this value of heat

286 release into equation (7) yields a magma replenishment rate, dV_m/dt, of $\sim$1.2 m^3 s^{-1}. With these

287   assumptions and values the amount of magma replenishment between 1994 and 2015 would be

288   ~7.8 x 10^8 m^3. Given that the maximum vertical cross-sectional area of the AML is ~6 x 10^3 m-

289   long x 100 m-deep, the amount of magma needed to sustain the hydrothermal system would

290   extend ~1300 m across-axis, more than four times the upper estimate of ~300 m suggested by the

291   2015 MCS data images, and well within the navigational precision of both the 1994 and 2015

292   surveys. If cooling and/or crystallization is greater as might be expected from hydrothermal

293   circulation a smaller magma replenishment rate is possible. For example, if the amount of

294   magma cooling is 100°C, with 50% crystallization, the resulting rate of magma replenishment

295   needed to sustain the 200 MW hydrothermal system would be 0.24 m^3 s^{-1} and the volume of

296   magma emplaced would be 1.6 x 10^8 m^3. In this scenario the expected across-axis width of the

297   AML would be ~270 m, which is of the same order as the putative AML width.

298

299   It is also possible, however, that magma replenishment is episodic even on a 20-year time scale

300   and that hydrothermal heat output would then wax and wane in that time frame. Finite width

301   dikes in layer 2B suggest discrete intrusion events every 10-100 years [*Head et al.*, 1996]. At an

302   intermediate spreading center such as the CRR magma replenishment is likely to be more

303   infrequent than at the fast spreading East Pacific Rise over long time scales. If the plume

304   represented the heat from a single replenishment event, the volume of magma needed to generate

305   the 200 MW of heat would scale with time since the event.

306

307   **5. Discussion**

308

309   CTTD data indicates the presence of a hydrothermal plume above the CRR, that has a heat

310   output of ~200 ±100 MW. MCS images have enabled estimation of AML dimensions and

311   magma replenishment characteristics at the CRR. Our modeling results assume quasi-steady state

312   behavior. However, the MCS data may, instead, be suggesting episodic AML replenishment. The

313   contrasting pattern of AML reflectivity between the 1994 and 2015 surveys (Figure 4) suggests

314   that the western region of the ridge axis is the current focus of magma replenishment, and that it

315   could possibly be disconnected from the eastern limb as a result of rapid, focused, hydrothermal

316   cooling. Alternatively, the two limbs may be joined, supplied via a single magma source, with

317   the apparent gap between the western and eastern limbs an artifact of out-of-plane interference

318   and scattering of seismic energy by the rugged seafloor topography above. The lack of a clear

319   across-axis reflection event from the AML suggests a narrow width perpendicular to the

320   spreading direction, whereby the AML appears to be a ribbon of magma extending ~6 km along

321   the ridge axis with a maximum width of 300 m, significantly narrower than AMLs observed at

322   other intermediate [e.g., *Van Ark et al.*, 2007] or the faster spreading ridges [e.g., *Kent et al.*,

323   1993].

324

325   The extent of the AML along axis suggests significant westward magma replenishment has

326   occurred, raising the question of whether the inferred volume of magma replenishment required

327   to maintain a 200 MW hydrothermal system can do so for two decades, or instead if the

328   replenishment process is more likely to be episodic. Assuming that magma is added to the AML

329   over its entire current length of ~6 km, we find that to maintain a 200 MW hydrothermal system

330   for 20 years, the across-axis width of the AML would have to range between ~270 and 1300 m,

331   depending on the degree of cooling and crystallization assumed. Given the estimated AML

332 width, it is possible that either the observed hydrothermal heat output is a result of

333 significant/enhanced cooling of a consistent magma replenishment, or a result of more recent

334 replenishment focused towards the western end of the ridge axis. Numerical models of two-phase

335 flow in NaCl-H_2O systems indicate that there is a lag time of years to decades between the decay

336 of heat input at the base of the system and changes in seafloor vent temperatures and heat output

337 [*Singh et al.*, 2013; *Choi and Lowell*, 2015]. Consequently, the currently observed heat output

338 may reflect an episode of magma replenishment in the recent past (years to decades), and the

339 westward extending AML reflectivity suggests, in turn, an apparently thin ribbon of recent

340 magma replenishment into the AML that has yet to spread in the across axis direction.

341

342 A new episode of magma input, associated with a phase of diking, may generate an event plume

343 [e.g., *Baker et al.*, 1987, 1998; *Lowell and Germanovich*, 1995]. In this case, the heat output and

344 ^{3}He anomaly recorded in the observed water column plume may reflect a transient event rather

345 than be an indication of quasi-steady-state hydrothermal heat flux. A repeat CTTD survey

346 conducted two weeks later in the same area (Figure 3b) failed to detect the plume which may

347 support a transitory cause or, more simply, a change in ocean currents or tidal flows may have

348 displaced it from its previously observed location.

349

350 One hundred and sixteen of the more significant microearthquakes recorded during the 2015

351 OBS survey were hand-picked, and their hypocenters projected onto a depth-converted migrated

352 image of line NG_Bb13 (Figure 6). These locations were estimated using the NonLinLoc

353 software (*Lomax et al.*, 2000) based on a 1D crustal velocity model derived from modeling of

354 both OBS and MCS gather travel time picks [*Wilson et al.*, 2019; *Robinson et al.*, in revision].

16

355   This analysis shows that the majority of these events recorded during a 21-day period are

356   distributed at or above the AML between 83°48′W and 83°52′W. Analyzing the distribution of

357   seismicity suggests that there are two principal event populations. The initial cluster of

358   seismicity, between Julian days (JD) 26-34, is located above and to the east of the gap between

359   the two AML limbs, and extends from AML depth to the seabed. It is not clear whether there is a

360   discernible migration in the depth of seismicity, either upward or downward, over the period of

361   this cluster. However, similar observations elsewhere [e.g., *Tolstoy et al.* 2008; *Dziak et al.*,

362   2007] correlate such seismicity with the existence of active, high-temperature hydrothermal

363   circulation within the upper crust that would transfer heat from the underlying AML. This

364   correlation between heat source and seismicity may, therefore, reflect hydraulic fracturing within

365   the hydrothermal circulation system [e.g., Wilcock et al., 2009]. Further, *Fontaine et al.* [2011]

366   predict that localized hydrothermal cells will cause along strike variation in the size of an AML

367   on a scale-length of hundreds of meters, so our estimate of the AML width under the CRR, based

368   on a single MCS line, even though repeated, is open to debate. Possible evidence for this

369   interaction is provided by the second cluster, between JD 35-47, which predominantly occurs

370   above the western AML limb and is confined to depths >5 km, suggesting that this population

371   may be related to changes in the AML volume. The apparent lack of seismicity between the

372   AML and the NTD may also suggest the presence of a cooling front, limiting eastward melt

373   migration.

374

375   Although our analysis of magma-hydrothermal interactions at the CRR suggests that magma

376   supply may be episodic even on a decadal scale, episodic magma supply likely occurs over much

377   longer time scales as well. Hence the ridge axis may, therefore, evolve through alternating

378   phases of tectonism and magmatic accretion [*Kappel and Ryan*, 1986]. This interpretation is

379   supported by off-axis observations at the CRR [*Wilson et al.*, 2019] which demonstrate the

380   variable crustal formation modes that have occurred at this ridge system over 7 Ma. We suggest,

381   therefore, that intermediate spreading ridge systems may represent a finely balanced

382   environment, where changes in the rates of magma supply, tectonic extension, and hydrothermal

383   cooling may shift the equilibrium state towards different end-member spreading modes.

384

385   **6. Conclusions**

386

387   The combination of water column data and repeat multichannel seismic surveys at the CRR axis

388   enables us to make a preliminary appraisal of magma-hydrothermal interactions at this

389   intermediate spreading ridge. The results suggest that current hydrothermal heat output at the

390   CRR may be the result of continuous or episodic magma replenishment, that has undergone

391   significant cooling by hydrothermal circulation. Alternatively, the observed hydrothermal plume

392   may represent a transient event such as an event plume associated with a recent input of magma

393   into the AML coupled with a phase of diking. In either case, the MCS data clearly show both

394   temporal and spatial changes in AML characteristics at the CRR axis on a decadal time scale,

395   and these changes may be reflected in corresponding changes in hydrothermal discharge.

396   Additional information on the state of the CRR hydrothermal system is required to determine

397   whether it is in a decaying or a growing phase, which can only be gleaned from a detailed

398   seafloor morphological and sampling study, supported by a high-resolution 3D volume seismic

399   survey to correctly map the location of the AML both along and across the ridge axis.

400

422

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599

600

Figure Captions

602

603   Figure 1. Swath bathymetry map of the Costa Rica Rift (CRR). Black dashed lines mark the

604   cruise track of JC114 in the vicinity of the CRR axis. Solid black lines show the locations of

605   MCS profiles NG_Bb13, 1268 and NG_G10; red triangles indicate OBS locations; blue and red

606   crosses indicate CTTD cast locations discussed in this study. Inset (top right) shows location of

607   the study area (blue rectangle) in the Panama Basin. Principal bathymetric and tectonic features

608   are labelled: the Cocos Ridge, the Galapagos Islands, the Carnegie Ridge, the Malpelo Ridge, the

609   Ecuador Trench, the Galapagos Spreading Ridge (GSR), the Inca Transform (IT), the Ecuador

610   Rift (ER), the Ecuador Fracture Zone (EFZ), the Costa Rica Rift (CRR), and the Panama

611   Fracture Zone (PFZ). The relative plate motion between the Cocos and Nazca plates is shown

612   (mm/yr) along with the location of the ODP site 504B.

613

614   **Figure 2.** Schematic of heat balance model linking axial magma lens heat content to plume heat

615   content showing the relationship of some of the important parameters.

616

617   **Figure 3.** (a) CTD/transmissometry (CTTD) casts along Costa Rica Rift axis showing decreased

618   transmissivity between 2500 m to 2800 m depth. Ridge axis is 3150 m depth. Red curve is a

619   mean of seven profiles (black curves); (b) Results from Δ^3He analyses from water samples taken

620   over the CRR at CTTD 6 (09-12-2014, blue points) and CTTD 55 (02-01-2015, red points). Note

621   the elevated value within the depth range of decreased transmissivity. (c) Abyssal stratification

622   over the ridge axis, where N^2 is a squared Brunt-Väisälä frequency. Black lines show individual

623   casts. Dotted and solid red lines show averages displaying higher and lower order data trends

624   respectively. Solid horizontal gray line indicates the top of the transmissivity and Δ^3He

625   anomalies, and change in slope of N^2, interpreted as representing the top of the plume. Dashed

626   horizontal gray line indicates the base of the transmissivity anomaly.

627

628   **Figure 4.** Seismic reflection images of the axial magma lens (AML) for MCS profiles shown on

629   Figure 1. (a) Line 1268 from the 1994 survey. (b) Line NG_Bb13 and (c) line NG_G10 from the

630   2015 survey. Black dots indicate the AML reflection at ~5.1-5.3 s TWTT. Comparing the

631   stacked image of the AML in (a) with that in (b), we can observe that AML extends westward

632   and its length increases from 2.4 to 6.0 km during the 21 years that separate the surveys.

633   Locations of the non-transform discontinuity (NTD), the intersections between N-S and E-W

634   lines and the average spreading rates over the past 4 My [*Wilson et al.*, 2019] between the Cocos

635   and Nazca plates are labelled.

636

637   **Figure 5.** 1-D five-layer velocity-depth model (a) and its corresponding reflectivity (b) used to

638   forward modelling a CDP gather [after *Wilson et al.*, 2019]. The black line denotes P-wave

639   velocity (V_p), the red line S-wave velocity (V_s) and the green line density (ρ). The solid and

640   dashed blue lines show the OBS and MCS inversion derived 1-D velocity structure at the ridge

641   axis respectively, and the dotted purple line shows the OBS forward modelling 1-D velocity

642   structure (all from *Wilson et al.*, 2019). (c) Synthesized waveforms and (d) observed records of

643   an example CDP gather (1217 from line 1268) with trace offsets incrementing every 25 m and

644   ranging from 187.5 m to 462.5 m. The seabed (water-bottom) and AML reflections are labeled.

645

646 **Figure 6.** Microseismicity at the CRR. (a) Swath bathymetry of the CRR. Inverted red triangles

647 indicate OBS locations used for picking and relocating earthquake locations. Dots are earthquake

648 hypocenters, colored by elapsed time in Julian days since the start of 2015. Black line shows the

649 location of line NG_Bb13. (b) Depth distributions of hypocenters across the ridge axis. (c) Depth

650 distributions of hypocenters along the ridge axis overlaid on a time-to-depth converted migrated

651 seismic image of line NG_Bb13. The majority of microearthquakes are located directly above

652 the AML. The location of the NTD is labelled.

653

654

655   **Table 1. Symbols and parameters**

656

Symbol	Meaning	Value/Units
A_d	Area of discharge zone	m^2
A_m	Area of AML	m^2
c_p	Specific heat of seawater	$4\text{-}5 \times 10^3 \text{ J kg}^{-1} \, ^\circ\text{C}^{-1}$
c_m	Specific heat of magma	$1.1 \times 10^3 \text{ J kg}^{-1} \, ^\circ\text{C}^{-1}$
F_0	Buoyancy flux	$m^4 \, s^{-3}$
g	Acceleration due to gravity	9.8 m s^{-2}
H	Hydrothermal heat output	Watts
H_m	AML heat content	J
k	Permeability	m^2
L	Latent heat of magma	$4 \times 10^5 \text{ J kg}^{-1}$
N^2	Brunt-Väisälä frequency	s^{-2}
Q	Volume flux of fluid	$m^3 \, s^{-1}$
T_m	Magma liquidus temperature	1200°C
T_v	Hydrothermal vent temperature	350°C
V_m	Volume of melt	m^3
z	Vertical coordinate	
Z^*	Maximum plume rise height	m
Greek symbols		
α	Thermal expansion coefficient of seawater	$1.5 \times 10^{-4} \, ^\circ\text{C}^{-1}$
α_d	Thermal expansion coefficient of hydrothermal fluid in discharge zone	$10^{-3} \, ^\circ\text{C}^{-1}$
δ	Thermal boundary layer thickness	m
λ	Thermal conductivity of magma	$2.0 \text{ W m}^{-1} \, ^\circ\text{C}^{-1}$
ρ	Fluid density	$kg \, m^{-3}$
ρ_0	Background seawater density	1000 kg m^{-3}
ρ_m	Magma density	2700 kg m^{-3}
v_d	Kinematic viscosity of hydrothermal fluid	$10^{-7} \text{ m}^2 \, s^{-1}$

657
658
659

Figure 1.

Plume
  Z* - Maximum plume rise height
  Fo - Buoyancy flux
  N - Brunt -Väisälä frequency

  H - hydrothermal heat output
  Q - Volume flow rate

Ad - Area of discharge zone

  δ - Thermal boundary layer

Axial Magma Lens (AML)
  Am - Area of AML
  Hm - AML heat content
  Vm - Volume of melt

662
663

Figure 2.

a)

b)

c)

Depth (m)

Transmissivity (%)

$\Delta\ ^3$He (%)

N^2 (x10^{-6} s^{-2})

□ 3º 18.127' N, 83º 33.964' W
□ 3º 21.149' N, 83º 54.853' W

664

Figure 3.

34

665

35

666

Figure 5.

a)

b)

Depth (km)

c)

NTD

AML

Depth (km)

Depth (km)

Elapsed time (Julian Day)

667

Figure 6.

37